ABSTRACT

The glutamate metabotropic receptor 4 (GRM4) locus is linked to susceptibility to human osteosarcoma, through unknown mechanisms. We show that Grm4−/− gene-targeted mice demonstrate accelerated radiation-induced tumor development to an extent comparable with Rb1−/− mice. GRM4 is expressed in myeloid cells, selectively regulating expression of IL23 and the related cytokine IL12. Osteosarcoma-conditioned media induce myeloid cell Il23 expression in a GRM4-dependent fashion, while suppressing the related cytokine Il12. Both human and mouse osteosarcomas express an increased IL23/IL12 ratio, whereas higher IL23 expression is associated with worse survival in humans. Consistent with an oncogenic role, Il23−/− mice are strikingly resistant to osteosarcoma development. Agonists of GRM4 or a neutralizing antibody to IL23 suppressed osteosarcoma growth in mice. These findings identify a novel, druggable myeloid suppressor pathway linking GRM4 to the proinflammatory IL23/IL12 axis.

SIGNIFICANCE: Few novel systemic therapies targeting osteosarcoma have emerged in the last four decades. Using insights gained from a genome-wide association study and mouse modeling, we show that GRM4 plays a role in driving osteosarcoma via a non–cell-autonomous mechanism regulating IL23, opening new avenues for therapeutic intervention.

INTRODUCTION

Osteosarcoma is an aggressive primary malignant tumor of the bone and a significant cause of cancer-related death in the young. Patients are commonly treated with multimodal approaches, including surgery and adjuvant chemotherapy. Few effective systemic therapies have emerged in the last four decades for relapsed or metastatic osteosarcoma (1, 2). Osteosarcomas represent a promising indication for strategies that target the immune system (2); however, a recent clinical trial...
using immune-checkpoint blockade has failed so far in the treatment of advanced osteosarcoma (3).

Hereditary factors play an important role, and osteosarcoma is a feature of families with rare mutations in TPS3, RB1, RECL4L, and BLM (4). A genome-wide association study (GWAS) investigating the role of common genetic variation identified a locus at 6p21.3 [rs1906953; odds ratio 1.57, 95% confidence intervals (95% CI), 1.35–1.83; \( P = 8.1 \times 10^{-7} \)] in the \( GRM4 \) gene with susceptibility to osteosarcoma (5), which was validated in two subsequent studies (6, 7). \( GRM4 \) (metabotropic glutamate receptor 4 or mGlur4) is a member of the group III family of G protein–coupled receptors that negatively regulates the cyclic adenosine monophosphate (cAMP)/protein kinase A (PKA) pathway. \( GRM4 \) plays a role in the central nervous system and is highly expressed in the cerebellum by cerebellar granule cells, but also by immune cells, and has been implicated in both neurodegenerative and autoimmune diseases (8, 9). Studies of the biological role of \( GRM4 \) in cancer are limited. Its expression has been associated with poor prognosis in several cancers, including malignant gliomas, colorectal cancer, and rhabdomyosarcoma (10), whereas \( GRM4 \) agonists have shown in vitro or xenograft activity in medulloblastoma (11) and glioblastoma cell lines (12), and recently in bladder cancer (13). In osteosarcoma, a small study has shown \( GRM4 \) expression correlates with better survival (14). Here, we sought to investigate the biological and therapeutic roles of \( GRM4 \) in vivo using genetic models of osteosarcoma.

RESULTS

\( GRM4 \) Gene–Targeted Mice Have Accelerated Osteosarcoma Development and Identify Role for Inflammatory Cytokine IL23

We first asked whether \( GRM4 \) had tumor-suppressive or oncogenic effects on tumor development. Wild-type (WT; \( n = 26 \)) or \( GRM4^{−/−} \) mice (\( n = 25 \)) were injected with \( ^{45}\)Ca, a low-energy \( \beta \)-emitter that localizes to bone (ref. 15; Fig. 1A; Supplementary Fig. S1A–S1C). Ionizing radiation is the strongest environmental risk factor for osteosarcoma in humans (4). Tumor latency in this model is consistently 10 to 12 months (16, 17). \( GRM4^{−/−} \) mice had accelerated tumor development [Fig. 1B; hazard ratio (HR) 0.41; 95% CI, 0.22–0.76, \( P = 0.0006 \); median survival in WT mice 89 weeks vs. 65 weeks in \( GRM4^{−/−} \) mice]. Outside the central nervous system, \( GRM4 \) is highly expressed by dendritic cells (DC), as well as CD4+ T cells (8). In the mouse osteosarcomas, we observed \( GRM4 \) is predominantly expressed by CD45+CD11c+MHCII myeloid cells, but not by tumor cells (Fig. 1C). Too few CD4+ T cells were detectable to characterize \( GRM4 \) expression (not shown).

\( GRM4 \) regulates DC expression of the cytokines IL1, IL6, IL23, and IL27 in experimental autoimmune encephalomyelitis (8). Using a standard strategy enriching for bone marrow DCs (18), \( GRM4^{−/−} \) DCs showed selectively increased expression of the related proinflammatory cytokines IL12 and IL23 relative to WT DCs (Fig. 1D). Sharing a common p40 subunit, both IL12 and IL23 are secreted by human and mouse DCs and tissue-resident macrophages in response to exogenous or endogenous signals (19, 20). Increased expression of IL23 is observed in many human cancers (21–23), whereas IL12 has potent antitumor activity (24). Primary \( ^{45}\)Ca osteosarcomas and allografted cell lines had high IL23 expression relative to normal bone, but ex vivo–cultured osteosarcoma cell lines did not express IL23 (Supplementary Fig. S2A and S2B). In addition, IL23 is not expressed within primary tumor cells (Fig. 1E). To show that these findings were not a function of a radiocarcinogen model, the expression of IL23 was also examined in osteosarcomas from genetically defined mouse models (Oxs/Cre Trp53/Rb and Oxs/Cre Trp53.1224 pRb mice, ref. 25; Supplementary Fig. S3A). Again, the majority of tumors had increased IL23 compared with normal bone. \( ^{45}\)Ca radiation-induced osteosarcomas from \( Grm4^{−/−} \) mice (\( n = 5 \)) have higher expression of IL23 compared with WT tumors (\( n = 6 \); \( P = 0.0358 \); Supplementary Fig. S3B). Flow-cytometry analysis of \( ^{45}\)Ca spontaneous tumors identified \( GRM4^{−/−} \) MHCII+CD11c+ cells as the predominant source of IL23 in the tumor microenvironment. To identify more precisely the tumor myeloid subpopulations and expression of \( GRM4, \) IL12, and IL23, we phenotyped osteosarcomas for infiltration of conventional DCs (cDC1: MHCII+CD11c+CD64 Ly6c−CD11b+ or cDC2: MHCII+CD11c+CD64 Ly6c−CD11b+) and monocyte-derived DCs (MoDC), defined as MHCII+CD11c+Ly6c−CD64+CD124+CD11b+ (Supplementary Fig. S4 gating strategy; ref. 20). In the OS18 allograft, the predominant source of IL23 was found to be from \( GRM4^{−/−} \) MoDCs (Supplementary Fig. S5). Similar results were observed in primary \( ^{45}\)Ca tumors (Fig. 1E; Supplementary Fig. S6A), and the non-radiocarcinogen K7M2 allograft tumors (Supplementary Fig. S6B). By contrast with IL23, IL12 was virtually undetectable in tumor-derived MoDCs, and neither IL12 nor IL23 was observed in conventional DCs. Taken together, these data suggest that both \( GRM4 \) and IL23 are expressed by MoDCs within tumors.

To determine whether osteosarcoma cells influence the expression of IL12 and IL23 in vitro, bone marrow–derived DCs (BMDC) were exposed to conditioned media from cultured mouse osteosarcoma cells (OS-CM). Lipopolysaccharide (LPS) was used as a positive control (26, 27). In WT BMDCs, LPS increased cAMP (Supplementary Fig. S7A) and IL12 and IL23. OS-CM significantly induced IL23 expression in BMDCs, while suppressing IL12 (Fig. 1F and G). The cAMP/PKA pathway mediates, and LPS increases cAMP whereas \( GRM4 \) decreases cAMP production (8). Consistent with an intermediate role for the cAMP/PKA pathway, forskolin, a cAMP agonist, recapitulated the effect of OS-CM by inducing IL23 expression by BMDCs (Supplementary Fig. S7B). \( GRM4 \) agonists are being developed for neurologic disorders, including depression and Parkinson disease (28). PHCCC [(–)-N-phenyl-7-(hydroxyimino)cyclopropa[b]chromen-1a-carboxamide] is a positive allosteric modulator of \( GRM4 \), whereas cinnabarinic acid (CIN) is an orthosteric regulator. Pretreatment with \( GRM4 \) agonists attenuated cAMP expression (Supplementary Fig. S7A) and suppressed LPS-induced (Supplementary Fig. S8A) or OS-CM–induced IL23 expression (Fig. 1H–K). PHCCC induced IL12 expression higher than that observed for LPS alone, but not OS-CM. PHCCC also downregulated IL23 in human peripheral blood DCs stimulated with LPS (Supplementary Fig. S8B). Collectively, these data support the interpretation that osteosarcoma cells repress IL23 production by MoDCs, an effect that is modulated by \( GRM4 \) signaling.
Myeloid GRM4 Regulates IL23 in Tumor Progression

Figure 1. Grm4−/− mice have accelerated osteosarcoma development. A, Schematic of the radiation-induced mouse model of osteosarcoma; mice at 28 days of age were injected with 1 μCi/g 45Ca intraperitoneally once weekly for 4 consecutive weeks and monitored for the growth of tumors. B, Kaplan-Meier plots showing that Grm4−/− mice (n = 25) are predisposed to the development of 45Ca-induced osteosarcomas compared with WT mice (n = 26; P = 0.0006). C, Flow cytometry analysis of WT 45Ca tumors reveals that GRM4 is predominantly expressed by tumor-infiltrating myeloid cells defined as CD45−, MHC class II+, CD11c+ (blue line) and with limited expression in tumor cells (CD45−, negative cells), dotted line; control fluorescence minus one (FMO), dashed line. A representative tumor is shown with ~19.4% of MHC class II+; CD11c+ cells positive for extracellular GRM4 expression. D, Grm4−/− BMDCs have higher transcript levels of Il23a and Il23b at baseline. Bone marrow was isolated from WT or Grm4−/− mice, cultured in the presence of IL4 and GMCSF for 7 days to enrich for BMDCs, and cytokine transcriptional profiling was conducted. Grm4−/−, blue bars; WT, gray bars; data are normalized to housekeeping genes. Values are means and SEM of triplicate determinations; duplicate experiments were performed. E, Flow cytometry analysis of a 45Ca WT osteosarcoma; tumor cells are defined as CD45−, Pan DCs CD11c+MHCII+, MoDCs (Supplementary Fig. S4 gating strategy). A representative tumor is shown. The crossbar shows gating for IL12 or IL23 FMO defining positive cytokine staining cells. F and G, BMDCs derived from WT mice have attenuated Il12 expression and increased Il23 expression when treated with OS-CM. WT BMDCs were treated with LPS 1 μg/mL or OS-CM for 24 hours, and transcript levels of cytokines were assessed using qRT-PCR as outlined in the Methods. GRM4 agonists suppress the expression of Il23 by BMDCs. H and I, BMDCs were treated with GRM4 agonists PHCCC or CIN (40 μmol/L) for 1 hour and stimulated with LPS at 1 μg/mL for 24 hours, and transcript levels of cytokines measured. J and K, BMDCs were treated with PHCCC (40 μmol/L) for 1 hour and stimulated with OS-CM at a 1:1 ratio for 24 hours, and transcript levels were measured. Data are means ± SEM, representative of three independent experiments. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001.
**II23 Gene–Targeted Mice Are Protected from the Development of Tumors**

Given that GRM4 suppresses tumor development (Fig. 1B), and IL23 is negatively regulated by GRM4, we tested whether IL23 itself had oncogenic properties in the osteosarcoma model. IL23p19−/− (II23−/−) mice were strikingly protected from tumor development, with 24/30 (80%) of II23−/− mice tumor-free at 104 weeks compared with 0 control mice at 90.7 weeks (Fig. 2A; HR 9.4; 95% CI, 3.3–27; P < 0.0001). II17−/− mice show no predisposition to or protection from the development of 45Ca-induced tumors. C, Forest plot of groups of 14–25 WT and litter-matched gene-targeted mice that were injected with 45Ca and then aged. Mice were monitored for tumor development for up to 2 years. Hazard ratio from log-rank test, 95% confidence interval, and Mantel–Cox test for significance compared with WT. ♦, published (see ref. 11).

**High IL23 in the Tumor Correlates with Worse Overall Survival in Humans**

We next examined the expression of IL23 in a series of human osteosarcomas using *in situ* hybridization. More than 60% of samples demonstrated focal staining for IL23A (p19) expression (12% high, 24% medium), whereas little staining was observed in normal human bone (NHB; Fig. 3A; Supplementary Fig. S10). In an independent cohort quantitated by qRT-PCR, increased IL23A expression was noted in tumors compared with NHB, accompanied by reduced IL12A (p35) expression. More than 70% of samples exhibited significantly increased expression of IL23A over NHB, with 53% having ≥2-fold increase and 34% having >5-fold greater expression. By contrast, IL12A (p35) transcript expression was significantly lower in tumor samples relative to NHB (Fig. 3B). Finally, high IL23 expression (≥8-fold) was associated with worse survival (Fig. 3C; HR 0.33; 95% CI, 0.06–1.69; P = 0.0427).

**IL23 and GRM4 Are Therapeutically Targetable in Osteosarcoma**

Both IL23 and GRM4 are potential therapeutic targets, and IL23 blockade has been successful in treating psoriasis (32, 33). The antitumor activity of a neutralizing antibody (16E5)
targeting the p19 subunit of IL23 (αIL23) was compared with a control antibody (αAGP3). Following implantation of osteosarcoma cells into the flank of the leg, mice were treated with αIL23 or αAGP3. IL23 inhibition moderately slowed tumor growth (P = 0.0425) and prolonged survival (P = 0.0322; Fig. 4A and Fig. B). Neutralizing IL23 significantly decreased intratumor IL23 transcript as well as downstream targets (transcripts encoding IL22, MMP9, and TGFβ), but not IL17; Supplementary Fig. S11; refs. 21, 34). Markers of cytotoxic T-cell activity, Gzmα and Cxcl9, were significantly increased in tumors following treatment with αIL23 (Supplementary Fig. S12). To enhance the single-agent activity of αIL23, it was combined with doxorubicin, one of the most active drugs in the treatment of osteosarcoma. These studies used PEGylated liposomal doxorubicin (DOX), which has a more favorable toxicity profile for treatment of relapsed patients (35). Targeting IL23 suppressed tumor growth compared with both controls and DOX-treated mice (Fig. 4C; P = 0.009). To test whether GRM4 also represented a potential therapeutic target, mice transplanted with osteosarcomas were treated with PHCCC or DOX. PHCCC significantly suppressed tumor growth (Fig. 4D; P = 0.0001) with a potency comparable to DOX, but without the weight loss associated with DOX, suggesting PHCCC was better tolerated (Supplementary Fig. S13). Treatment with PHCCC was associated with increased IL12 transcript levels (Supplementary Fig. S14A and S1B).

Similar effects were observed with another specific GRM4 agonist, LSP2-9166 (Supplementary Fig. S15). Taken together, these data support the therapeutic potential of targeting the GRM4–IL23 axis (Fig. 4E). Neither an IL23 blocking antibody nor GRM4 agonists affected the growth of primary osteosarcoma cells cultured ex vivo, consistent with a key role for the host immune system in mediating their antitumor effects (Supplementary Fig. S16).

**DISCUSSION**

Cancer immunoediting studies over two decades suggest the immune system has secondary modifier effects on tumor development relative to the contribution of cell-autonomous, classic tumor suppressors and oncogenes (36). Here, we present direct human and mouse genetic evidence for a non-cell-autonomous role for GRM4 and IL23 within MoDCs in spontaneous tumor development. Strikingly, the magnitude of the effect of loss of GRM4 is comparable with the loss of the canonical tumor suppressor RB1. The modest disease association of polymorphisms in GWAS, presumably due to weak effects on gene expression, does not predict the biological or therapeutic effect due to complete loss-of-function mutations in mice. Of the 17 gene-targeted genotypes tested, the size of the oncogenic effect of IL23 in tumor development was marked. Although the oncogenic effects of IL23 have been reported in multiple cancer types (2, 21, 22, 37), it is interesting that subjects with psoriasis, an autoimmune disease driven by IL23, are specifically at risk of osteosarcoma and chondrosarcomas (HR 4.97; 95% CI, 2.32–10.62; P < 0.0001; ref. 38).

We propose that tumor-infiltrating MoDCs responding to inflammatory signals in the tumor microenvironment secrete IL23, contributing to an immune-suppressed environment. GRM4 and IL23 are primarily coexpressed within monocytic dendritic cells, and do not appear to be expressed by tumor cells. This is consistent with our previous observations (39), although we cannot exclude the role of other stromal cells in tumor development. GRM4 activation downregulates IL23 and suppresses tumor growth. In human osteosarcomas, tumor-infiltrating myeloid cells, including dendritic cells and macrophages, connote a worse survival outcome (40). DCs comprise diverse progeny of the myeloid lineage, including antigen-presenting cells (APC) required for efficient activation of T cells and maintenance of immune tolerance (41, 42). APCs are best known in cancer through their pivotal role in therapeutic vaccination strategies (43). Distinct DC populations have shown opposing effects on tumor immunity, driving antitumor immunity or contributing to immune nonresponsiveness in cancer (20). The understanding of myeloid subpopulations within tumors and their functional role is a rapidly evolving field (20, 42). Our data linking GRM4 to IL23 build on emerging evidence that glutamate signaling regulates IL23 expression (44), probably via GRM4 (8). It is important to note that IL23 is likely regulated by other mechanisms than GRM4, and also that GRM4 has actions independent of IL23.

There are significant therapeutic implications of these findings. To date, immune-checkpoint inhibitors targeting PD-1/PD-L1 have been disappointing in osteosarcoma (3).
The therapeutic effect of both IL23 antagonists and GRM4 agonists appeared comparable in our system to doxorubicin, one of the most active drugs currently used for the treatment of osteosarcoma. The fact that both Grm4−/− and Il23−/− mice apparently develop normally suggests drugs targeting these genes may be well tolerated. IL23 antagonists are already approved for the treatment of psoriasis, with favorable toxicity profiles (33). Our data suggest the balance of IL23:IL12 is important, because IL12 alone has potent antitumor activity (24). The first-generation agent IL23 antagonists (e.g., ustekinumab) targeted both IL23 and IL12 through a shared p40 subunit and may be less effective cancer therapeutics than second-generation agents selectively targeting the p19 subunit of IL23 (e.g., tildrakizumab and guselkumab; ref. 45). Of note, GRM4 agonists not only down-regulate IL23, but also increase IL12. Foliglurax (46), a novel positive allosteric activator of GRM4, is currently in phase II trials for Parkinson disease (NCT03162874A). In summary, our findings identify a non–cell-autonomous pathway linking GRM4 to the proinflammatory IL23–IL12 axis, with the potential to be therapeutically targeted in osteosarcoma.

**METHODS**

**Mice**

Inbred wild-type C57Bl6/J (C57BL/6 WT) and C57BL6 GRM4-deficient (Grm4−/−) mice were purchased from The Jackson Laboratory; C57BL/6 Il23p19-deficient (Il23−/−), C57BL/6 Cldd-deficient (Cldd−/−), C57BL/6 Ifnaro1-deficient (Ifnaro1−/−), C57BL/6 Ifnaro2-deficient (Ifnaro2−/−), C57BL/6 Il1β-deficient (Il1β−/−), C57BL/6 perforin and Ifnγ-deficient (pfnγ−/−), C57BL/6 Ccl24.pdl1−/−, C57BL/6 Tnfα-deficient (Tnfα−/−), C57BL/6 Bim-deficient (Bim−/−), C57BL/6 Cd73-deficient (Cd73−/−), C57BL/6 Cld2-deficient (Cld2−/−), C57BL/6 Cas2-deficient (Cas2−/−), and C57BL/6 Il1r-deficient (Il1r−/−) mice were either generated using C57BL/6 embryonic stem cells or back-crossed to at least 10 generations to C57BL/6. All mice were genotyped using published protocols. Mice were bred at Australian BioResources (Moss Vale, NSW, Australia) and...
maintained at the Garvan Institute Biological Testing Facility, with all animal experiments carried out according to guidelines contained within the NSW (Australia) Animal Research Act 1985, the NSW (Australia) Animal Research Regulation 2010, and the Australian code of practice for the care and use of animals for scientific purposes (8th Edition, 2013, National Health and Medical Research Council, Australia) and approved by Garvan/St. Vincent’s Animal Ethics and Experimentation Committee (approval number 15/21, 15/30, 18/31, 18/38). Some experiments were performed at the Peter MacCallum Cancer, Melbourne, Australia; all procedures using mice were reviewed and approved by the Peter MacCallum animal ethics experimentation committee.

**Mouse Models of Osteosarcoma**

The experiments using the radiocarcinogen model were conducted as previously described (15, 16). Briefly, mice were injected with 1 μCi/g 4Ca (GE Healthcare) or 0.9% saline intraocularly at 28, 35, 42, and 49 days postpartum. Mice were aged and monitored for signs of tumorogenesis (limping, paralysis, loss of condition, poor feeding or grooming, or weight loss) twice weekly for up to two years. Mice developed tumors in the spine (70%) and limbs (18%), and then pelvis, cranium, scapula, and clavicle (12%). In some instances, X-ray imaging was conducted using a Faxitron system. Mice were sedated with isoflurane inhalation and scanned.

**Tumor Implantation Model and Treatment Studies**

Osteosarcoma cell lines were derived from tumors from 4Ca experiments (OS18, OS25); these cell lines generate osteosarcoma when implanted into C57BL/6 mice. The OS cell lines were derived by culturing tumor pieces in Minimum Essential Medium with alpha modification, 10% heat-inactivated fetal calf serum, 1x penicillin/streptomycin, 2 mmol/L Glutamax, and 1 mmol/L sodium pyruvate until a monolayer grew out. Cells were passaged 20 to 25 times and were checked for Mycoplasma contamination by qRT-PCR, and aliquots were frozen. New aliquots were thawed for each experiment and passaged up to 8 times. OS cell lines cultured in vitro were mixed with 1:1 Matrigel:media and a total volume of 100 μL (10⁶ cells) was injected subcutaneously in the flank. Mice were monitored for tumor growth relative to adjacent non–tumor cell injected leg using digital calipers (United Precision Machine, Inc.). Mice were treated as described in the legends; mice were treated intraperitoneally with anti-IL23p19 (ail23) or control antibody (αGAP3) at 500 μg/mouse (Ampgen) weekly, liposomal doxorubicin (Calyx) 2.5-5 mg/kg or PHCCC in vehicle DMSO 20% 10 mg/kg or LSP2-9166 10 mg/kg in saline as described in the legends.

**Gene-Expression Analysis and Statistical Methods**

Transcript levels of cytokines were determined using quantitative RT-PCR. Total RNA was extracted from cells using TRIzol and Qiagen RNEasy Mini Kit per the manufacturer’s instructions. RNA was converted to cDNA using standard techniques. Real-time RT-PCR was carried out using SYBR Green (Applied Biosystems) according to the manufacturer’s instructions using an ABI Prism 7000 Sequence Detection System. All primer sequences are listed in Supplementary Table S1. Statistical analysis was performed using GraphPad Prism software. Human osteosarcoma samples with correlative survival data were collected and approved under ethics application project CMT 2018-010 approved by HREC CRB Centre Léon Bérard, Lyon, France.

**Cytokine Assay**

Cell culture media from control and treated cells were frozen at –80°C. The concentration of cytokines was quantitatively determined using Cytometric Bead Array (CBA) Cytokine Kits, mouse or human (BD Biosciences), as per kit instructions. A standard calibration curve was established for each kit. The maximum and minimum detection limits for cytokines were 1 to 5,000 pg/mL.

**Flow-Cytometry Immune Cell–Infiltration Analysis**

Tumors were washed in PBS and cut into 1-mm³ pieces, and tissue was digested in DMEM supplemented with 2% FCS and 5 mg/mL collagenase A for 50 minutes at 37°C. Cells were passed through a 70-μm mesh and labeled with surface antibodies and intracellular antibodies. Mouse splenocytes were used as positive controls for immune cells. Cells were analyzed using a Fortessa system (BD Biosciences). Data were analyzed using FlowJo software. Antibodies are listed in Supplementary Table S2.

**Histology**

Tissue was fixed in 10% neutral buffered formalin, embedded in paraffin, and sectioned and stained with hematoxylin and eosin, via routine method. Human bone and osteosarcoma tissue microarrays were purchased from Biomax (BO244B, OS804). In situ hybridization was carried out using probes for mouse and human IL23-encoding RNA (ACD Bio-Techne). Slides were scanned on ScanScope XT (Aperio).

**DC Enrichment and Stimulation**

BMDCs were generated as described (Abcam protocol modified from ref. 18). Briefly, bone marrow was flushed out of mouse tibia and femur and single cell suspension–plated in the presence of 50 ng/ml GM-CSF and 50 ng/ml IL4 (PeproTech); 80% of the medium was removed, and new medium added at day 3; assays were conducted on day 7. Flow cytometry analysis of enriched dendritic cells was conducted. Cells were plated in 6-well plates and treated.

**Statistical Analysis**

Statistical analysis was performed using GraphPad Prism software (V7.0a, GraphPad). Values are reported as means ± SEM. When comparing two groups, P values were calculated using two-tailed Student t tests. For time to event and survival analysis, P values for the Kaplan–Meier survival curves were calculated with a log-rank (Mantel–Cox) test. Significance was conventionally accepted at P values equal to or less than 0.05. For multiple treatment group comparisons, significance was determined by one-way analysis of variance, followed by the Tukey post hoc multiple comparisons test, where *, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001.

**Data and Materials Availability**

All data are available in the main text or the supplementary materials.

**Disclosure of Potential Conflicts of Interest**

J.-P. Pin reports receiving a commercial research grant from CisBio Bioassays and has ownership interest in patents on mGLu4 assays and pharmacological compounds. E.G. Demicco is a consultant/advisory board member for Bayer. M.W.L. Teng has received honoraria from the speakers bureaus of Bristol-Myers Squibb, Roche, and Merck. M.J. Smyth reports receiving commercial research grants from Bristol-Myers Squibb and Tizona Therapeutics, has ownership interest (including patents) in Tizona Therapeutics, and is a consultant/advisory board member for Tizona Therapeutics and Compass Therapeutics. D.M. Thomas reports receiving commercial research support from Amgen. No potential conflicts of interest were disclosed by the other authors.

**Authors’ Contributions**

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Infiltrating Myeloid Cells Drive Osteosarcoma Progression via GRM4 Regulation of IL23

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